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Strategies and Methods for the Energy Efficient Production of Electric Drives

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Abstract

This paper presents methods and experiments for the assessment and evaluation of energy efficiency strategies for manufacturing processes in the field of electric drives production. First, the system for the Least Energy Demand Method will be explained. The basic idea of this calculation is the comparison and evaluation of energy efficiency based on the ratio of the theoretically required energy consumption to the measured energy consumption. Using these values as well as further derived indicators for energy efficiency, the main energy consumers within the field of electric drives production are identified. Subsequently, these processes are analysed and optimized to achieve major energy saving instructions. From an energy point of view during the stator production chain, especially the impregnation process and the joining process have to be optimized as, in the here presented measurements, the impregnation process amounts to more than 80 % of the cumulated energy demands. Moreover, the process of joining insulated copper wires of the stator windings to corresponding cables shoes is optimized, as it shows strong energy saving potentials. Additionally, the power consumption values within the state of the art joining process are varying strongly thus leading to higher load peaks within the production line, which have to be reduced. Regarding energy efficiency within the manufacturing of permanent magnet synchronous rotors, the process of magnet assembly also has to be evaluated. It can be subdivided into magnet manufacturing, logistics, magnetization and assembly. A major part of the energy used in this process is accounted for by means of transportation, especially when considering that magnetized magnets need larger packaging volumes and weights due to the ferromagnetic shielding and spacers to support handling of the magnet bodies. Thus, the energy efficiency can be increased considerably by shifting the magnetization step directly to right before the assembly step. In addition, energy can be saved by optimizing the magnetization process according to the magnetization strategy and the interaction of all process parameters, such as capacity of the magnetizer, inductivity and size of the magnetizing coil, magnet size, material and coating.

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Keywords: Energy efficiency, Electric drives production, Manufacturing strategy, Least Energy Demand Method

1. Introduction

Regarding the climate change, resource shortage, and rising energy prices, energy efficiency is becoming increasingly more important in all areas of life. With systems such as the EU energy label, the EU Energy Star labeling system for energy-efficient office equipment [1] and the CO_2 efficiency class for cars [2], end users have been given a number of tools for purchase decisions, which enable a comparison of offered products within a product group in terms of energy consumption and pollutant emissions. However, the mentioned systems simply evaluate the energy consumption during the operation of the respective product. So far, there are no approaches that allow a comparison of the products with respect to the energy efficiency of their manufacturing processes. [3] For the identification of highly efficient

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production structures a comparison to derive specific saving potentials has to be possible. In order to gain the maximum use of the available potential, it is important that the energy efficiency can be assessed, compared and evaluated not only across product categories, but also across industry sectors and enterprises. Only this approach makes it possible to identify highly efficient production structures and specific saving potentials that can be a positive example and reference. As a result, the defined relative energy efficiency gives information about the level of target achievement of the absolute energy efficiency and it enables a statement about the theoretically possible potential for energy savings. [4]

2. The Least Energy Demand Method on process level to evaluate the electric drives production processes

2.1. KPIs and methods to evaluate the energy efficiency

Regarding the climate change, resource shortage, and rising energy prices, energy efficiency is becoming increasingly important in all areas of life. With systems such as the EU energy label, the EU Energy Star labeling system for energy-efficient office equipment [1] and the CO_2 efficiency class for cars [5], end users have been given a number of tools for purchase decisions, which enable a comparison of offered products within a product group in terms of energy consumption and pollutant emissions. However, the mentioned systems simply evaluate the energy consumption during the operation of the respective product. So far, there are no approaches that allow for a comparison of the products with respect to the energy efficiency of their manufacturing processes. It has been shown that certain important aspects limit the comparability of almost all energy indicators. Each energy index, which is intended to provide an indication of the energy efficiency in the manufacturing process, must include energy consumption values in any form. However, in many instances there is no sufficient data basis, since no continuous measurements are carried out [6]. There is no measure that manages to consider all influence factors. Accordingly, a comparison seems to be only possible if the comparative indicators have been determined under the same conditions. Therefore, the aim should be to document the characteristics of the influencing factors in order for them to be correctly interpreted when compared to the aim of identification of optimization potentials [7]. The most important method requirements for evaluating the energy efficiency were defined as follows: general requirements, warranty of the over-all comparability, and operative applicability. The Least Energy Demand Method as the most promising approach fulfills all defined requirements. The basic system consists of the Least Energy Requirement, the measurement of the energy consumption, the development of KPI's, and the cross-comparison.

2.2. The calculation of the least energy demand

The calculation system for the Least Energy Demand Method is divided into three steps. The first minimum value results from the basic operation, which is the basis for the implementation of the transformation process and independent from technology and machine. By means of the basic operation the applicable technologies for this purpose, which will be implemented by equipment eventually, are determined. The analysis of constituent dependencies shows that a minimum value calculation may be carried out step-by-step. Consequently, the minimum energy demand for the implementation of the basic operation, their technological implementation, and the technological implementation according to the equipment, can be calculated. The resulting minimum values refer to the physical, technological as well as to the real minimum. [3]

Physical minimum: The Energetic Physical Minimum (EPM) describes how much energy is required for chemical or physical laws to induce an intended transformation through a defined basic operation on or in the object under consideration. The physical minimum is calculated only on the basis of the specifications of the input and output material (Em) by summing up the specific energy consumptions of the material (1). [3] [4]

$$E_{PM} = \sum_{i=1}^{n} (E_m)_i \qquad (1)$$

Technological minimum: The Energetic Technological Minimum (ETM) describes the energy demand, which is minimally required to perform a basic operation by a technology. Here, the technology to perform the transformation process is also taken into account. From the chosen technology, consequently, the specific calculation method of the minimum value and the process specifications are determined. To calculate the minimum value, shown in equation 2, the optimization of all technological specifications (Et) in terms of minimum energy consumption are required; however, the equipment-related losses are not yet taken into account. In general, the technological minimum is calculated by adding the physical minimum to the sum of the specific technological energy consumptions (ET). [3] [4]

$$E_{TM} = E_{PM} + \sum_{i=1}^{n} (E_t)_i \qquad (2)$$

Real minimum: The Energetic Real Minimum (ERM) describes the energy demand, which is minimally required to perform a basic operation by a technology with a consumer. The consumer specifications consist in particular of the machine specific losses of efficiency due to the energy conversion. The real minimum is an extension of the technological minimum of the equipment and is calculated by extending the calculated technological minimum to the losses of the equipment (Ee), shown in equation 3. [3] [4]

$$E_{RM} = E_{TM} + \sum_{i=1}^{n} (E_e)_i \qquad (3)$$

Combined Consideration: The relative energy efficiency (REE) compares and evaluates the energy efficiency of technical service provision. The minimum values of all three kinds of minima can serve as a basis and can be set in relation to the energy consumption measured (E_C). However, the focus and the statement of the calculated REE varies for each selected reference value. [3]

Therefore, it is recommended to use the real minimum value as basis for the calculation of the REE for the comparison and evaluation of the energy efficiency of the technical service provision. This is justified by the fact that the REE, based on the real minimum, focuses on the real savings potential, which can be exploited if necessary.

Furthermore, it can be assumed that the REE varies less for different products, which increases their comparability and reduces the resignation threat that is expressed in negative outcomes. [3]

The Least Energy Demand Method is now applied to the manufacturing process of the stator of an electric motor.

2.3. Overview of the stator manufacturing

Table 1 shows eight process steps of the stator production using the listed manufacturing techniques. For the sheet cuts generation, the CO_2 laser-cutting process for the sheet packaging, the bonding varnish process for the slot base insulation, the powder coating technology for the winding generation, the needle winding process for electrical joining, the hot-crimping technology, and for impregnating, the atmospheric dip impregnation process is investigated energetically. For the slot base insulation and impregnation the auxiliary processes of preheating and hardening are considered, which run convective at the slot base insulation and inductive at the impregnating process.

Table 1. Overview of stator manufacturing.

process step	used method
sheet cuts generation	CO_2 laser-cutting
sheet packaging	bonding varnish process
slot base insulation	convective preheating powder coating convective hardening
winding generation	needle winding
electrical contacting	hot-crimping 1 hot-crimping 2
forming of the winding head	not considered
testing	not considered
impregnating	inductive preheating atmospheric dip impregnation inductive hardening

2.4. Comparison of the individual process steps in their energy efficiency

Fig. 1 shows the ratio of the measured energy consumption and the real minimum of energy for the individual process steps in the manufacturing process of a stator. The calculated least energy demand, based on the approach of the real minimum, for several process steps is shown as the lower bar.

The absolute required and measured energy values are shown beside. Both values are given in Wh above the bars. For the comprehensive visualization of the relative saving potentials for different processes, in this case an unscaled diagram is used. The different bars of the energy demand represent reference points to determine the relative energy efficiency of the analyzed processes. The relative energy efficiency indicates the potential for improvement that can be achieved by optimizing the process. Next to the efficiency the value of the measured energy consumption should be considered to estimate the impact of an efficiency optimization of the process.

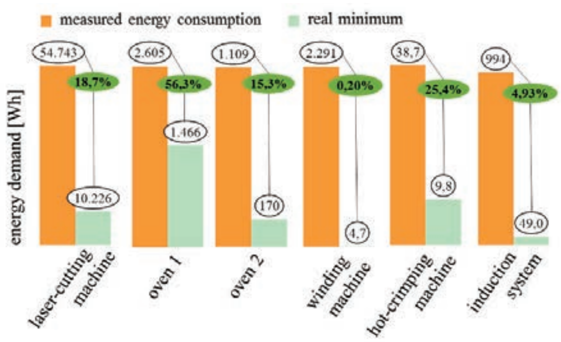

Fig. 1. Energy efficiency evaluation of process steps of a stator production

2.5. Conclusion of the energy efficiency evaluation of the stator process chain

The practical application of the Least Energy Demand Method to determine the REE values at the perspective levels, process to sector, leads to specific result values at the individual levels. The resulting percentage values determine the degree of target achievement compared to the intended energy minima and shows theoretically possible saving potentials [8]. The REE values based on the real minimum in the manufacturing process of a stator vary between 0,2 % and 68,2 %. The data analysis, by means of the described method, enables the assignment of optimization potentials to the causes of the occurred losses that are shaped by material, method, and machine following the value-added chain. Here, energy saving potentials, which are based on non-value adding operations such as waiting, maintenance and setting activities, are caused due to an insufficient production structure. These potentials can be revealed by using a combined material and energy flow simulation presented in [9], [10] and [11]. According to [12], this non-process-related energy waste can be reduced by up to 20 %. Aside of this energy waste reduction strategy, genuine process-related energy potentials have to be revealed. For this purpose, several processes of the electric drives production chain and the belonging energy corresponding measures are evaluated with the measurement device presented in [13]. Here, at first two interesting stator process steps and the corresponding investigations are presented. Afterwards, main rotor processing steps, such as magnet handling and assembly, are investigated and further opportunities to improve the energy efficiency are revealed.

3. Energy assessment and saving Potentials within impregnation technology

Insulation systems perform valuable tasks within electric machines, making them indispensable for modern high-performance drives. [14] Regarding the evaluation of energy consumption and efficiency of the associated processes, very little scientific work is known; and most often projects address the optimization of well-known but outdated process variations [16]. The most recent disruptive innovation in the field of insulation and impregnation technology can be considered the Electrical/UV process which already dates back to 1995. [15] Future process chains require modern, fast and efficient technologies in this field, but innovation is yet obstructed by self-made barriers, which arise from the lack of process knowledge and valid assessments of investment cost and process benefits. [17] Consequently, the presented research in this field focusses on the comparison of existing process variation with recent advances in insulation and impregnation technology.

Current complexity regarding the variety of available impregnation processes as well as curing methods and materials impedes general assessment of the various manifestations. This results in the presence of numerous insufficient combinations of processes and resin materials, leading to an excessive need of resources. Regarding the fact that impregnation processes already account for as much as 80% of the total energy need for the production of an electric stator [18], reducing consumption within this profession forms a valuable lever in the aim of reducing overall costs and energy needs. The majority of resources are deployed during the process of resin curing, as impregnation processes rely almost exclusively on thermosetting resins based on epoxies, polyesters, and poly-imides. Advanced and innovative impregnation processes must focus on the general reduction of energy being applied to curing. Within the research project E|Solation the most commonly used processes as well as novel heating technologies without widespread industrial implementation are being evaluated based on energy usage and process times by using a standardized stator geometry (see Fig. 2).

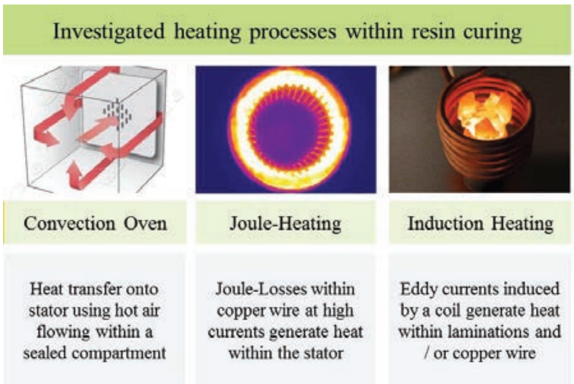

Fig. 2: Investigated heating technologies within this paper

Technologies presented in this paper include convection heating based on a hot, moving air flow as well as the established method of joule-heating, generating heat through electric losses induced by high currents within the copper wire of electric drives. Both processes are widely implemented in the field of electric drive production. Additionally, induction-based heating as a representative of newer technologies will be compared to the previously described methods. Using the two subsequently described methods heat is generated within the stator of the electric drive itself, thus making the heating process more efficient. Joule-Heating is often used in combination with UV-Radiation to accelerate surface-near curing and will be evaluated in this form.

3.1. Energy savings using joule- and induction heating

Energy transfer regarding convection is influenced by numerous amounts of factors including air flow speed, direction of air flow, heated mass and surface finish. As equation 4 shows, heat transfer is highly dependent of the heat transfer coefficient α. With rising counts of heat transfers through altering media, overall efficiency suffers significantly since every transfer means a loss of energy. Regarding convection heating this results in a maximum efficiency of about 40% [18]. Since both joule and induction heating generate heat without the need for transfers between different media, thermal efficiency is superior, ranging above 80% in general [19].

$$Q = \alpha * A * (T_1 - T_2) * \Delta t \quad (4)$$

In order to evaluate actual saving potentials and energy efficiency over a complete impregnation process as well as general benefits (e.g. cycle time), all heating technologies are combined with a mutual dipping process in addition to a unified stator geometry to ensure comparability. The stator being tested has an outer diameter of 120 mm and a mass of 8 kg. All processes were evaluated using lab-systems. Scaled systems for industrial applications are expected to use less power per stator. Fig. 3 shows the outcome of the process evaluations.

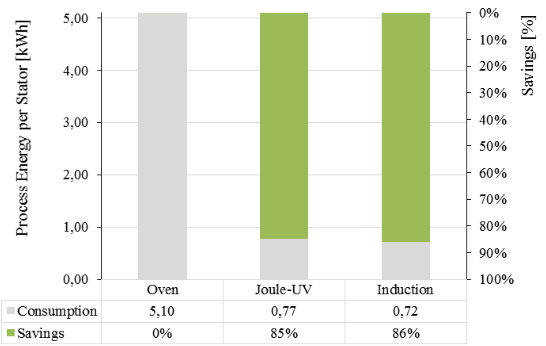

Fig. 3: Energy saving potentials within curing processes.

By using joule-heating in combination with UV-light curing, energy consumption per stator can be reduced by 85% in comparison to the common, convection oven based process. It has to be noted that industrial scaled oven processes perform significantly better than the displayed graph, but still range high above joule- and induction-based heating. The implementation of induction heating is able to reduce energy consumption even more, although to a lesser extent. It has to be noted that induction experiments were performed within a heating fixture that – in opposition to the other processes in focus – has not been optimized for the impregnation of electric drives. Yet, the outcomes show that impregnation processes can still be improved and heating processes especially bear a lot of potential for electric drives production.

3.2. Further saving potentials in induction heating

As stated, fixtures for induction heating have still to be optimized for the use within electric drives production. Currently, it is common to adjust inductor size to accommodate the largest possible part being heated within a production. However, heating efficiency decreases significantly if the inductor is larger than the part being heated within. [20] Fig. 4 shows the efficiency drop over rising inductor diameter.

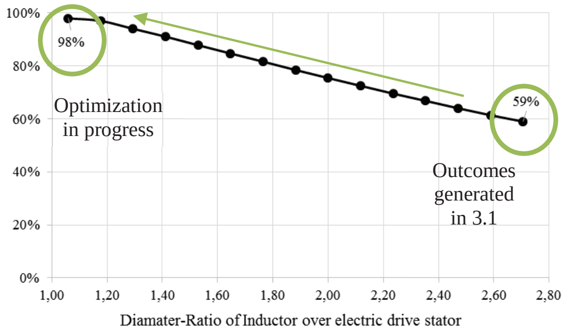

Fig. 4: Heating efficiency over inductor diameter ratio

The outcomes stated in 3.1 were generated using an inductor/stator ratio of 2.7, resulting in a heating efficiency of only 59%. Future investigations will focus on inductor size ratings < 1.3 with an expected rise in efficiency of about 60%.

4. Energy saving potentials within the joining process

In the field of electric drives production one major technology for generating an electrical connection between the single engine coils is the joining of insulated copper wire bundles with suited tubular cable lugs.

For this step, the industrial state of the art process is the thermo-crimping technology illustrated in [21]. Here, the thermal heat to strip the insulation from the copper wires is generated by the energization of the crimping electrodes. Thus, the needed stripping temperature is induced indirectly in the electrodes and afterwards transported to the insulation via heat transfer processes.

Simultaneously, in addition to the stripping process, the crimping joint is shaped by a hydraulic actor generating a force fitted connection between the copper wires and the corresponding cable lug.

Another technology for performing the regarded joining task is the ultrasonic crimping process presented in [22] and [23]. Within this technology, the cable lug and the copper wires itself are heated up by the use of high frequency mechanical oscillations generated by piezo elements.

Analogous to the thermo-crimping process, this technology also preforms the cable lug reshaping step coincidently to the copper wire stripping. For this purpose, the sonotrode is embedded flexibly, allowing the possibility to deform the cable lug.

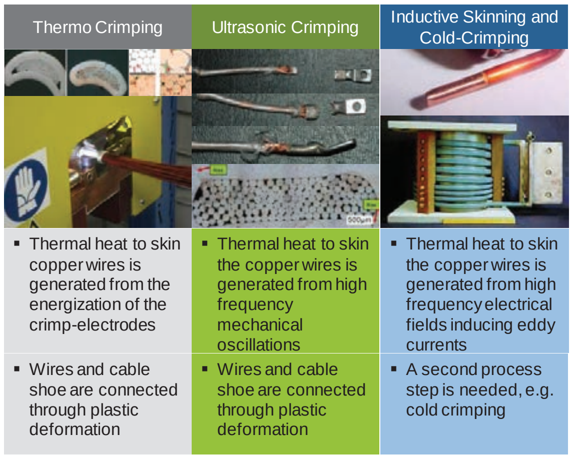

Fig. 5 Potential joining technologies

The technology discussed last is the inductive skinning process, which utilizes high frequency electrical fields to induce voltages within the copper wires leading to high currents and, consequently, heating processes. Here, due to the skin and proximity effects within the copper wires, the stripping process efficiency rises with growing frequencies of the electric fields. This technology implicates the strong disadvantage of the cable lug deformation process, which has to be performed in a following production step. However, using electrical frequencies of at least 200 kHz, the inductive skinning process seems to enable strong energetic saving potentials.

4.1. Energy saving potentials within the thermo-crimping

Within the thermo-crimping technique, varying process parameters influence the energy consumption. One major saving strategy evaluates the influence of proper equipment-related parameters like the electric heating power, the number of current pulses, the time of each current pulse and the deforming pressure. According to [24] this saving strategy strongly impacts the process energy consumption. Here, compared to the industrial standard process a savings potential of 43 % was evaluated, whereby the mechanical stability of the resulting joints was even improved. Another energy saving possibility is the variation of the shape and the material of the crimping electrodes, as the needed energy to skin the copper wires strongly depends on the resistance of these electrodes (5).

$$Q = I^2 \times R_{electrodes} \times t \quad (5)$$

Corresponding to the results presented in [25], the consideration of the energetic point of view within the electrode material choice leads to energy saving potentials of up to 40 %. However, although the resulting joints feature comparable or even better joint quality values, e.g. contact resistances and tensile forces, it is not economically sensible to implement all of these potentials. The reason for the little practicality is that the energetically best electrode materials show huge wearing effects.

Due to this fact, tungsten turned out to be a suitable substitute for the industrial standard material molybdenum, as it provides energetic saving potentials of about 20 % (see Fig. 6) and at the same time allows the production of a large number of good quality joints without wearing itself out.

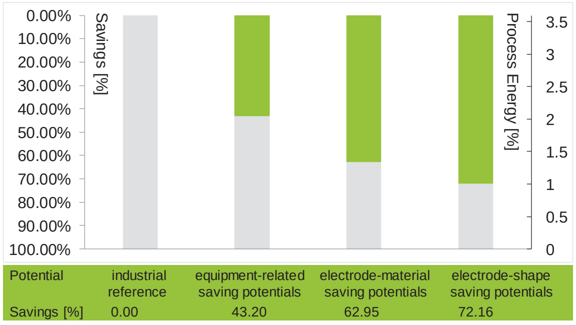

Fig. 6: Energy saving potentials within the thermo-crimping process

The last possibility for reducing the process energy consumption within the thermo-crimping technique is the variation of electrode shapes.

Here, the industrial state of the art electrode produces banana-shaped crimping joints, which feature changing quality characteristics across the joints' profiles due to the asymmetric current density within the crimping process.

For this reason symmetric crimping electrodes are investigated that feature the same current density in both electrodes leading to a large reduction of waring effects. Moreover, the symmetric thermal stress of the upper and lower part of the crimping joint provides another energy savings potential of about 10%.

4.2. Energy saving potentials due to changing joining technologies

The main related disadvantage of the thermo-crimping technology is the indirect heating of the workpieces leading to high energy consumptions and strong tool wearing. Therefore, the remaining two technologies are investigated energetically, as they are based on direct heating of the copper and insulation materials. Thus, their technological minima indicate huge energy saving potentials.

To evaluate these reduction opportunities, the industrial standard sample probes are manufactured by using the ultrasonic crimping and the inductive skinning method.

Here, the inductive skinning method is combined with a cold crimping process using a 100 kN servo-electric press. The evaluated energetic saving potentials in comparison to the industrially used process are shown in Table 2.

Table 2. Overview of energetic saving potentials using alternative joining techniques.

Technology	Thermo-crimping	Ultrasonic Crimping	Inductive Skinning
Saving potential [%]	72	94	88

The identified values illustrate huge saving potentials. Consequently, future research activities focus on the qualification of these techniques by improving process stability.

5. Optimizations within the magnet assembly process

Aside from the stator manufacturing processes as mentioned above, the rotor assembly process promises a considerable energy optimization potential.

The whole process chain contains cutting, stacking, magnetizing, magnet assembly, and magnet fixing. The magnet processing consists of magnet manufacturing, transportation and magnetizing. Regarding the non-thermal processes transportation and magnetizing are to be optimized.

5.1. Energy calculation tool for magnet logistics

The optimization potential in the transportation chain lies in the difference of the packaging volume of magnetized and non-magnetized magnets. Since magnetic interactions between magnets and other ferromagnetic material present a challenge in handling such parts, measures must be taken to, on the one hand, simplify magnet handling in the production line and, on the other hand, to avoid damage to other goods within the shipment.

Commonly, this is done by inserting spacers between single magnets in a stack and between stacks. Furthermore, the packing contains cavities for holding the stacks in place. For shielding against magnetic fields, the package is wrapped in ferromagnetic material with a high magnetic permeability. [27] These measures enlarge the size of the packing up to quintuple the packing dimensions of non-magnetized magnets.

To optimize the transport chain a software tool based on DIN EN 16258 [28] using free-access databases has been developed to meet the requirements of the electric drives production.

This tool enables the calculation of greenhouse gas emissions caused by the transportation of the magnets. The algorithm implemented in the software tool combines all possible routes and transport vehicles and calculates an optimized route with the minimum energy demand depending on the magnetization status of the shipped magnets. As an input the geometrical magnet data, the magnet quantity as well as the locations of the magnet supplier, several service providers, and the customer are to be given.

Fig. 7: Optimized transport chain with detailed energy data

The result is a detailed transportation chain with information concerning the energy demand of all transport sections.

5.2. Energy efficiency of the magnetization process

The magnetization process of rare-earth permanent magnets is done via creating a strong magnetic field with a coil and an impulse magnetizer. Therefore, a high current strength (approx. 7,5 kA, depending on material and dimensions of the magnet body) is needed, which causes a large amount of the heat inside the coil, even if only a current pulse length of ~1 ms is applied. Additionally, eddy currents inside the electrical conductive material, such as sintered neodymium iron boron, cause a reduction of the magnetic field in some areas inside the magnet and thus lead to insufficient and inhomogeneous magnetization.

To compensate for this undesired effect, the pulse is formed in an aperiodic sequence by using a free-wheeling thyristor parallel to the coil. This measure leads to more heat inside the coil, since the whole charge of energy from the impulse magnetizer is converted into heat. [29] Consequently, the impulse magnetization process is associated with low energy efficiency, need for cooling and wear of the magnetization coil.

Table 3. Magnet data of an exemplary NdFeB material [26]

Material	Magnetizing field strength H_S[kA/m]	Magnetizing flux density μ_0 H_S[T]	Magnetizing energy A_C[Ws/cm³]
NdFeB	2.500	1,3	4

In order to reduce these undesired effects, an optimization in terms of magnetization strategy and precise knowledge of the exact energy demand of the magnet system to be magnetized is needed. Since the energy demand of the coil for creating the required magnetic field strength for magnetizing NdFeB magnets to their magnetic saturation is 1670 times higher than the physical demand of the magnetic material, the energy savings potential becomes obvious.

Investigations at the FAPS institute show that the magnetic saturation of a stack of identical samples is reached earlier in comparison to the magnetization of single magnets.

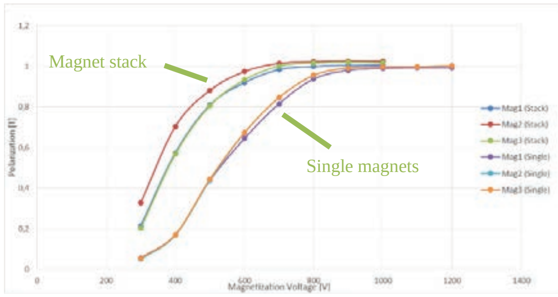

Fig. 8: Saturation curves of single magnets and stacked magnets in comparision

The test was done by magnetizing 3 N30EHS grade magnet bodies with a volume of 3,1 cm³. To record the saturation curve the impulse magnetizer was charged to an initial magnetization voltage of 300 V. Following the magnetizing, the polarization of the single magnets was measured with a Helmholtz-Coil and a fluxmeter.

For the next iteration, the magnetization voltage was increased by 100 V. Fig. 8 shows the energy savings potential by stacking magnets while magnetizing. The saturation voltage of single magnets is 1100 V and as follows 20 % higher than the saturation voltage of the magnet stack. Consequently, the energy demand for magnetizing single magnets can be reduced by 75% when magnetizing three magnets simultaneously in a stack rather than to magnetize single magnets individually.

6. Conclusion

In conclusion, this paper shows the energy saving potentials during the process chain of the electric drives production. Based on the Least Energy Demand Method, these potentials can be detected equitable of the origin. For the joining and impregnation technologies different process alternatives are shown.

These improved technologies offer the opportunity of a real energy savings potential of up to 75% along the value chain. Furthermore, additional approaches are shown, most importantly, the savings potential during the distribution of permanent magnets, which energy efficient drives.

Moreover, the magnets can be produced more energy efficient and are improving the whole life cycle of electric drives.

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